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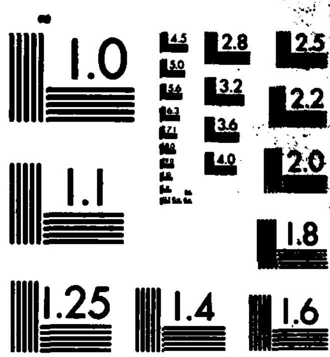
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FEASIBILITY OF TIME DOMAIN WAVE FORM SENSORS FOR THE MEASUREMENT OF DUST INDUCED ELECTROMAGNETIC NOISE

Science Applications International Corporation
Corporate C3 Program Office
P.O. Box 371
Stow, MA 01775-0371

23 January 1985

Technical Report

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This work evaluates the performance of extremely wide-band time domain electromagnetic pulse sensors which can be used to measure the waveform of dust-induced electromagnetic noise. Wide-band analog transducers (antenna) may consist of simple center-fed dipole elements suitably impedance loaded along their length to provide a traveling-wave current distribution. Established techniques are used to analyze the performance of such a device and it is concluded that suitable sensors are well within the state-of-the-art. Keywords:

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SECTION 1

INTRODUCTION

1-1 BACKGROUND

This report summarizes work performed by Science Applications International Corporation (SAIC) under Defense Nuclear Agency contract number DNA001-84-C-0372, Task #2, on the transient response of electromagnetic field sensors. This report is one in a series of reports describing SAIC's experimental design, deployment and results for the Dust Induced Noise (DIN) Program. The objective of the DIN study is to investigate the impact of dust induced noise on various military communication systems. This objective is met by recording the analog noise waveform in several 600 KHz wide bands spanning the MF through UHF portions of the radio spectrum. Since the noise signals are bandpass filtered in the recording process, the recorded signals do not faithfully reproduce the complete time domain waveform. In order to examine the characteristics of the full time domain signal in detail, in principle at least, an infinite-bandwidth recording system is required. SAIC has therefore been tasked to investigate the feasibility of very broadband sensors, and this report summarizes the results of that effort. The reader should bear in mind that the experimental and data analysis portions of the DIN Program are directed at the communication system impact of DIN, not at high-fidelity recording of the time domain waveform for purposes of investigating the fundamental physical mechanisms involved in the DIN process. This study is therefore strictly a feasibility study that addresses the single issue of whether or not suitable electromagnetic field sensors are available that will provide adequate fidelity to fully reproduce the transient DIN pulses.

1-2 PROBLEM STATEMENT

DIN is highly impulsive in nature. A typical time series (amplitude versus time) recorded at a DIN event illustrates the "spikey" nature of the noise field generated by internal arcing within the dust cloud lofted by surface or near-surface high-yield detonations. In many respects, DIN resembles the atmospheric noise produced by local and distant thunderstorm activity, although the two phenomena are almost certainly characterized by different statistics. Depending upon the signals levels generated during a DIN event, there may be a severe impact upon military communication systems operating in all portions of the radio spectrum. The assessment of communication system impact is accomplished by recording analog noise waveform signals in passbands whose width in the frequency domain is similar to that of a typical communication system. This experimental approach, however, cannot provide adequate resolution of the time domain pulse to support studies of the fundamental physics of DIN generation because of the inherent band-limited nature of the recording process.

In order to fully characterize the DIN process, it is necessary to record faithful reproductions of the complete time domain waveform during a number of DIN events. The electromagnetic field sensor in this application must produce, as nearly as possible, an exact replica of the radiated noise signal. To the extent that the sensor fails to reproduce the transient radiated pulse accurately, the time domain waveform measurement will be in error. The antennas used in the current DIN experimental apparatus are typical communication antennas, i.e., standing-wave (resonant) structures whose bandwidth is adequate to accomodate noise signals within the recording system passband. The antennas (sensors) required for a full time domain reconstruction of the radiated noise pulse, on the other hand, must exhibit extremely wide bandwidth without resonances. Communication antennas and time-domain field sensors are therefore very different in nature. Field sensors, for example, are designed with little or no consideration of gain and directivity, and certainly without any attempt to reject out-of-band interfering signals. These same attributes, of course, are key design objectives for communi-

cation antennas.

The antennas that are used to sense the radiated noise signal as a propagating electromagnetic field are passive, analog transducers that convert the measured signal into a voltage or current at their terminal ports. The performance of these devices is determined by their transmit and receive transfer functions, which, in turn, depend upon the sensor geometry and electrical parameters (characteristic impedance, effective electrical length and impedance loading along the sensing element). The purpose of this work is to investigate the feasibility of designing field sensors whose bandwidth is sufficiently large to faithfully reproduce the complete DIN time domain waveform. The calculations summarized in this report show clearly that such sensors are available and that the design considerations are well understood.

SECTION 2

THEORETICAL CONSIDERATIONS

The transmit and receive transfer functions, $S_t(f)$ and $S_r(f)$, respectively, for an antenna are given by [1]

$$S_t(f) = jkS_{10}e^{-jkr}E_t(f,r)/ra_0(f) \quad (1)$$

and

$$S_r(f) = b_0(f)/E_r(f) = 2\pi S_{01} \ . \quad (2)$$

In Eqs. (1) and (2), f is the frequency, S_{ij} are the device's scattering matrix elements, k is the free-space wavenumber, and r is the radial distance from source to observation point. The transmitted and received electric field strengths are E_t and E_r, respectively, with phasor amplitudes $a_0(f)$ and $b_0(f)$. Throughout this report, the assumed time dependence $\exp(j\omega t)$ is suppressed. And, following standard notation, j is the imaginary unit $\sqrt{-1}$.

The receiprocity theorem for antennas imposes the following relationship between the scattering matrix elements S_{01} and S_{10}:

$$\eta_L S_{01}(0) = -\eta_0 S_{10}(0) \ , \quad (3)$$

where η_L is the antenna load admittance, and η_0 is the admittance of free space. The constraint in Eq. (3) establishes a relationship between $S_t(f)$ and $S_r(f)$. The general conclusion is that S_t is proportional to the first partial time derivative of S_r, as long as η_L is real and frequency independent. In this work, of course, the emphasis is on the receive

transfer function, which may be calculated directly. Eq. (3) becomes useful when the sensor's far-field transmit characteristics have been calculated or measured.

Consider a linear dipole sensor with physical length 2h and diameter D as shown in Figure 2-1. A locally plane wave with wave vector $\vec{k}$ is incident upon the dipole whose orientation coincides with the direction of the incident electric field vector $\vec{E}$. For different orientations, the dipole output, which appears as a voltage V_0 between terminals 1 and 2, is multiplied by a cosine pattern factor (cosine of the included angle between the dipole axis the the incident field vector). A current is induced in the dipole by the propagating wave field that has the following traveling-wave form:

$$I(z) = V_0[1-|z|e^{-jk|z|}/h]/60\Psi(1-j/kh) \quad , \tag{4}$$

where

$$\Psi \cong 2[\sinh^{-1}(2h/D)-C(kD,2kh)-jS(kD,2kh)] + j(1-e^{-j2kh})/kh \quad . \tag{5}$$

In Eq. (4), C(x,y) and S(x,y) are the generalized cosine and sine integrals, respectively, defined by

$$C(x,y) = \int_0^y (1-\cos\sqrt{u^2+x^2})/\sqrt{u^2+x^2} \; du \tag{6}$$

$$S(x,y) = \int_0^y \sin\sqrt{u^2+x^2}/\sqrt{u^2+x^2} \; du \quad . \tag{7}$$

The dipole drive-point impedance $Z_0=V_0/I(0)$, and the dipole internal impedance per unit length, Z_i, for the structure of Figure 2-1

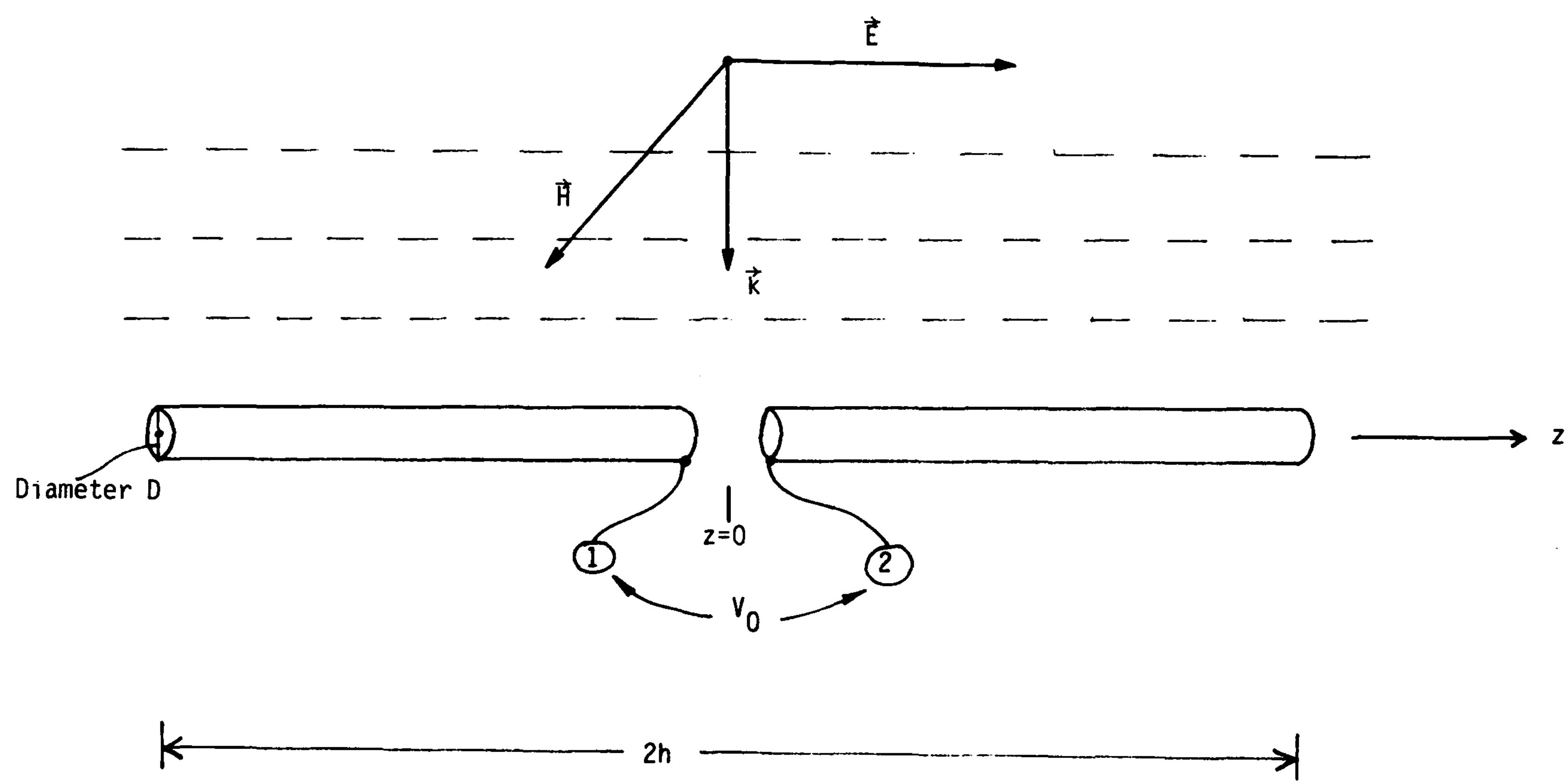

Figure 2-1. Dipole electric field sensor illuminated by plane wave field

are given by

$$Z_0(f) = 60\Psi[1-j/kh] \tag{8}$$

and

$$Z_i(z) = 60\Psi/(h-|z|) \quad . \tag{9}$$

The effective electrical length of the dipole sensor, which is frequency dependent, differs from the physical length of 2h and is given by

$$\begin{aligned} h_e(f) &= \int_{-h}^{+h} I(z)dz/I(0) \\ &= 2(1-jkh-e^{-jkh})/k^2h \quad . \end{aligned} \tag{10}$$

Each of the parameters, h_e, Z_i and Z_0, enters into the calculation of the transmit and receive transfer functions in Eqs. (1) and (2) via the scattering matrix elements S_{01} and S_{10}. Since each of these parameters is frequency-dependent, the sensor response is also frequency-dependent. An ideal sensor (perfect fidelity) would exhibit a flat (constant) transfer function at all frequencies; but, of course, no actual transducer does. By properly designing the sensor, however, the traveling-wave current form in Eq. (4) may be preserved over an extremely wide frequency range resulting in essentially flat response. In order to recover the non-resonant current distribution in Eq. (4), the dipole must be impedance-loaded along its length in accordance with the prescription of Eq. (9). Failure to properly load the sensor results in a standing wave current pattern whose resonant characteristics result in wide fluctu-

ations in the sensor transfer function with frequency. The impedance-loading method, therefore, is essentially a broadbanding technique which removes unwanted resonances from the transducer structure.

An example of the results attainable with this method is shown in Figure 2-2 in which the receive transfer function is plotted as a function of frequency for the dipole structure of Figure 2-1 with various loading impedances. Figure 2-2 shows clearly that extremely wideband performance (1 KHz to 1 GHz) is possible with proper element loading. Depending upon the specific application, the response may be tailored to the spectral characteristics of the measured waveform by appropriately introducing high or low frequency rolloff. The results in Figure 2-2 apply only to impedance-loaded dipoles, not to resonant antenna structures used in communication systems. Thus, the transducer discussed here is useful for high-fidelity wide bandwidth pulse recording where the objective of the measurement program is to faithfully reproduce the time domain pulse waveform. This sensor is not at all useful for communication purposes, however, since it lacks gain, directivity, and out-of-band signal rejection. If the objective of a measurement program is to assess the communication system impact of DIN or other similarly impulsive noise, then the high-fidelity wideband time domain sensor is inappropriate because it does not realistically model the actual performance of the communication link.

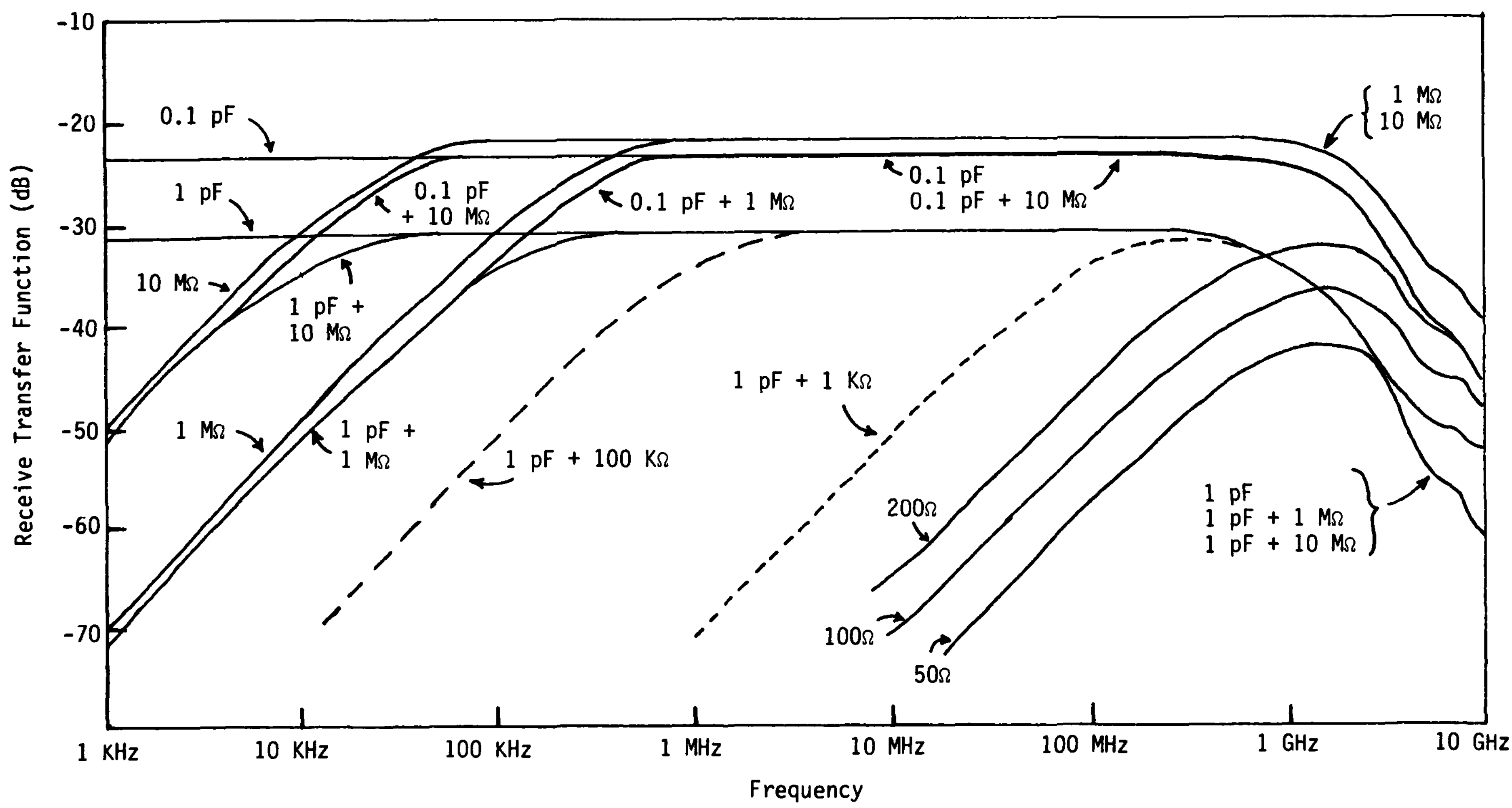

Figure 2-2. Computed receive transfer function vs. frequency for various impedance loadings

SECTION 3

CONCLUSIONS

Dust induced noise waveforms may be recorded for two different purposes: assessment of communication system impact as a source of external interference, or investigation of the fundamental physical processes involved in DIN based upon an examination of the detailed time domain noise waveform. In order to accomplish the first of these two objectives, the electromagnetic field sensors that are employed in the DIN experiment should be communication system antennas either of the type actually employed in communication systems or of the type used for radio noise measurements as described in CCIR Volume 1. In order to accomplish the second objective, the electromagnetic field sensor must exhibit flat response over an extremely wide bandwidth, so that it is impractical to use communication type antennas.

This report summarizes the design considerations and calculated performance of one type of wideband electromagnetic field sensor - the impedance-loaded center-fed linear dipole. Although other types of sensors exist that exhibit similar broadbandedness, the dipole sensor is the simplest and serves to illustrate the feasibility of designing and deploying a sensor with the requisite performance. The state-of-the-art clearly supports the objective of making high-fidelity recordings of DIN waveforms, at least as far as the field transducer is concerned.

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ATTN: H. Brode, Chairman SAGE
ATTN: L. Schlessinger

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Physics International Co
ATTN: Document Control

R & D Associates
ATTN: C. Knowles
ATTN: C. Mo
ATTN: Document Control
ATTN: M. Grover
ATTN: W. Karzas

R & D Associates
ATTN: W. Graham

Rand Corp
ATTN: B. Bennett

Raytheon Co
ATTN: G. Joshi

Raytheon Co
ATTN: H. Flescher

RCA Corp
ATTN: G. Brucker

Rockwell International Crop
ATTN: D/277-060, 031-BB17
ATTN: J. Burson
ATTN: J. Erb

Rockwell International Corp
ATTN: B. White

Rockwell International Corp
ATTN: B-1 Div Tic, BAOB

Rockwell International Corp
ATTN: F. Shaw

S-CUBED
ATTN: A. Wilson

Sanders Associates, Inc
ATTN: R. Despathy

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Science & Engrg Associates, Inc
ATTN: V. Jones

Science Applications Intl Corp
2 cy ATTN: J. Garrity
2 cy ATTN: R. Formato

Science Applications Intl Corp
ATTN: W. Chadsey

Singer Co
ATTN: Tech Info Center

Sperry Corp
ATTN: M. Cort

Sperry Corp
ATTN: Tech Lib

Sperry Corp
ATTN: D. Schow

SRI International
ATTN: A. Whitson
ATTN: E. Vance

Teledyne Brown Engineering
ATTN: F. Leopard
ATTN: J. Whitt

Texas Instruments, Inc
ATTN: D. Manus
ATTN: Tech Lib

Transients Limited Corp
ATTN: D. Clark

TRW Electronics & Defense Sector
ATTN: H. Holloway
ATTN: L. Magnolia
ATTN: O. Adams
ATTN: R. Plebuch
ATTN: W. Gargaro

United Technologies Corp
ATTN: Chief Elec Design

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